CRYOGENIC PUMPING SYSTEM FOR THE BTEV PIXEL DETECTOR
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Abstract

The current design of the BTeV Vacuum System is based on measurements of the gas load of the 5% model. The expected gas loads of water 10^{-2} torr L/sec and nitrogen 10^{-4} torr L/sec are used to obtain the required pumping speeds. Note that this is the gas released from the surfaces at the room temperature, for the detector with cryopanels that cool the vacuum vessel, the outgassing rate should be much lower. The cryopanels and the cooled cable strain relief structure shield the thermal radiation coming from the vacuum vessel wall and keep the detector at a reduced temperature. The required pumping system for water and nitrogen to bring the detector pressure lower than $1 \cdot 10^{-7}$ torr is designed not counting on this expected lower outgassing rate and not counting also on the outgassing rate natural decline after weeks under vacuum. The following surfaces at the liquid nitrogen temperature pump water: the cold block assembly, the two cryopanels, and the thermal shield of the liquid helium cryopumps. Four cryopumps cooled by liquid helium, shielded by metal plates at the liquid nitrogen temperature and located inside the vacuum vessel give the pumping speed required for nitrogen. A procedure to pump down and to regenerate the detector is given.

1 Vacuum System Parameters

The pumping requirement for the BTeV Pixel Detector is based on the gas load measurements of the 5% model [1]. The outgassing rate of the model at room temperature was measured $5 \cdot 10^{-4}$ torr L / sec. It was mainly water. For the entire pixel detector, at room temperature, the expected outgassing rate is 10^{-2} torr L / sec (by multiplying the measurement by twenty). The vacuum pumping system will consist of surfaces that are cryogenically cooled. The amount of cold surfaces required to pump water and to pump nitrogen is calculated considering the density and flow of the particles inside the vertex detector. The reason for this method of analysis is because the temperature throughout the vacuum vessel is not uniform. Whenever the temperature in the system is the same everywhere, the concepts of gas throughput, conductance and speed can be used to describe the state of a vacuum system. The throughput in a series circuit is constant only if the circuit is isothermal. Particle flow, however, is constant in a non-isothermal system.

The spurious interactions depend on the gas density in the interaction region. This density is $5.3 \cdot 10^{-9}$ mole / m^3 when the pressure is $1.0 \cdot 10^{-7}$ torr and the gas temperature is 300K. **The pumping system must keep the density of the gas inside the vertex detector lower than $5 \cdot 10^{-9}$ mole / m^3 regardless of the temperature.** The outgassing rate of 10^{-2} torr L / sec at the room temperature is equivalent to a particle flow released inside the vertex detector of about $5 \cdot 10^{-7}$ mole / sec.

The number of water molecules, having density n_w and average velocity v_w, reaching the unit surface of the cryopanel per unit time is

$$\Gamma_w = \frac{n_w v_w}{4} \qquad (1)$$

The temperature of the water molecules inside the vacuum vessel is higher than the average between 300 K (warm vessel wall) and 77 K (LN2 cold surfaces), because the water molecules having low kinetic energy have high probability to remain trapped on the cold surfaces. Assuming T = 240 K the average velocity is

$$v_w = \sqrt{\frac{8kT}{\pi m_w}} = 530\, m/\sec \qquad (2)$$

The water molecule density n_w reaches the steady state value when the flow of molecules sticking on the cryopanel surface is equal to the one released by the outgassing process ($\Phi_w = 5\cdot 10^{-7}\, mole/\sec$)

$$\Phi_w = c_w A_w \frac{n_w v_w}{4} \qquad (3)$$

The water condensation coefficient c_w is the ratio between the flow of molecules trapped on the cold cryopanel surface (A_w) and the total molecules flow arriving on it.

The pumping speed of the cryopanel is

$$S_w = c_w A_w \frac{v_w}{4} \qquad (4)$$

Usually the pumping speed is given assuming that the gas to be pumped is at room temperature. The average velocity of the water molecules at 300 K is 594 m/sec.

The major source of error, on the calculation of molecule density n_w, comes from the lack of knowledge of the water condensation coefficient c_w. We will obtain c_w from the measurement of the cryopanel pumping speed, inletting a know flow of water molecules into the same vacuum vessel used for the 5% model measurements. Let us now use the assessment $c_w \approx 0.4$ obtained from the summer 2002 measurements, when a know water leak inside the vacuum vessel was not available and we used the water released inside the vessel by the outgassing process. From the (3) we have that the cryopanel surface must be greater than 1.9 m^2 to keep the density lower than

$n_w = 5 \cdot 10^{-9}\, mole/m^3$ when the molecule flow released into the vacuum vessel is $5 \cdot 10^{-7}\, mole/\sec$ and the average velocity is $530\, m/\sec$.

2 Description of the Vacuum System

The vacuum system is made up of two pumping systems. A set of liquid helium cooled surfaces will pump gases such as nitrogen and hydrogen that are not condensable on a surface at the LN2 temperature. A set of liquid nitrogen cooled surfaces will pump water vapor. Figure 1 shows the components for half of the vacuum pumping system within the vacuum vessel.
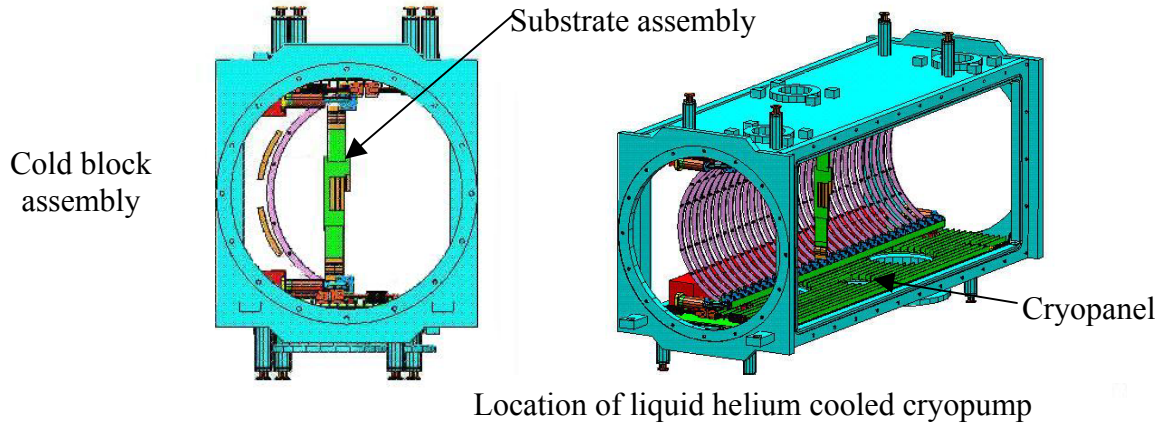

Figure 1 – Components of the Vacuum System for the Pixel Detector

Non-condensable gases are pumped by four liquid helium cooled pumps. The space that the cryopumps would take is shown in as red boxes in the corner of the vacuum vessel in Figure 1. The water pump is made of several components. There are two cryopanels located on the top and bottom of the vacuum vessel. The cold block assembly acts as a water pump. The four cryopumps also have radiation shields that are cooled by liquid nitrogen and thus also as water pumps.

2.1 Pump for non-condensable gas

To pump non-condensable gases on the cryopanel surface at the LN2 temperature, such as nitrogen, we consider the option of installing, inside the vertex detector vacuum vessel, four liquid helium cryopumps (Fig. 2). The option of using commercial cryopumps has been investigated. Due to the limited space around the vacuum vessel due to the magnet, the conductance any piping leading from the vacuum vessel to a remotely located cryopump is not adequate to remove the non-condensable gas. This leaves the requirement that the cryopump be located directly on the vacuum vessel. It has been shown that using four commercial cryopump (two on the top and two on the bottom wall of the vacuum vessel) the total pumping speed for nitrogen is about 2500 L/sec [2]. Once the vacuum vessel is installed within the magnet, the cryopump is not accessible for maintenance. As a result, it is not possible to use commercial cryopumps because they require maintenance service every 10,000 hours.
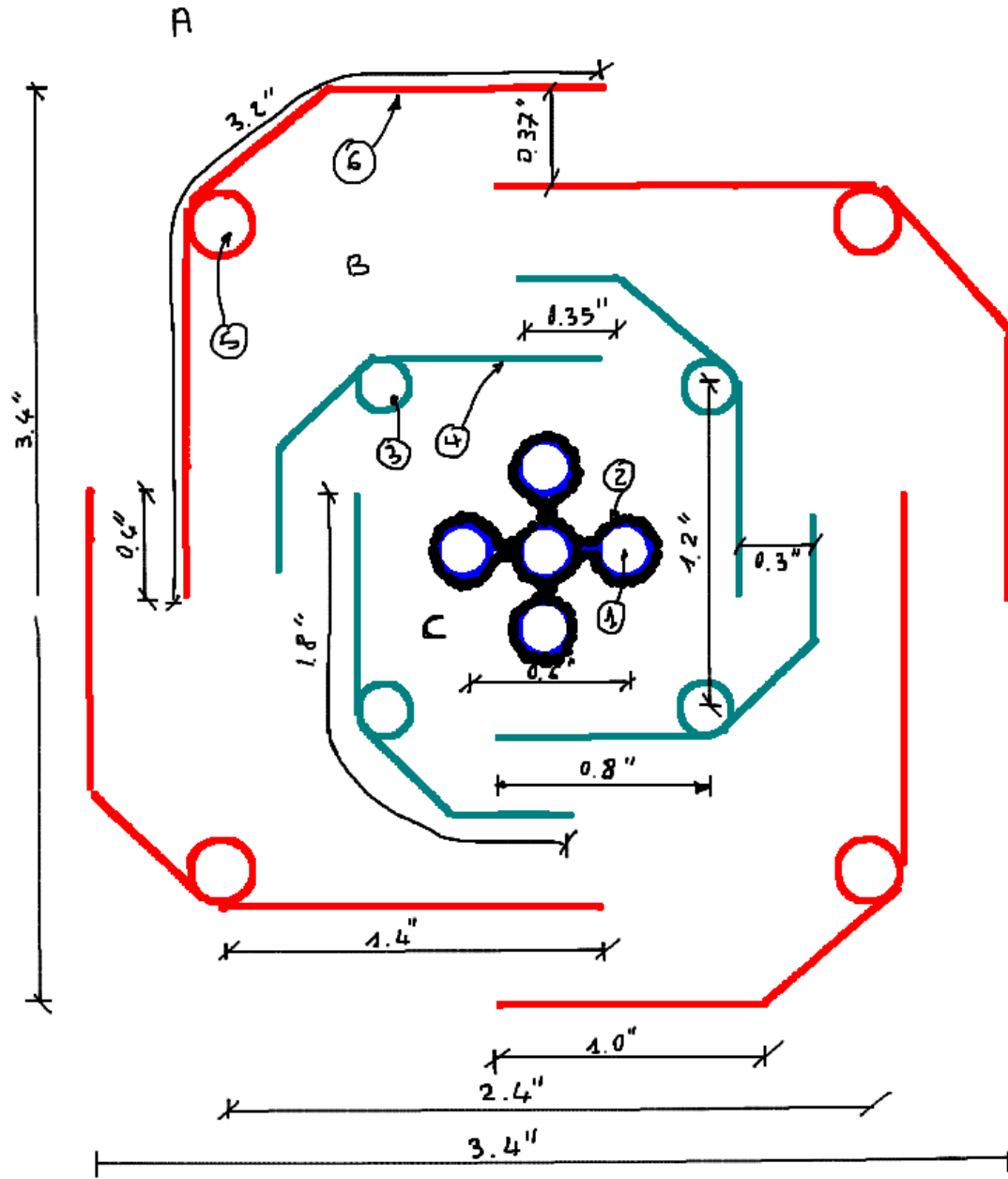
Figure 2. Three-stage cryogenic pump: {1} 0.2 inch stainless steel pipes carrying liquid helium (4.2K), {2} Charcoal sorbent, {3} 0.2 inch stainless steel pipes carrying gaseous helium boil-off (20K), {4} Highly oxidized copper plates, {5} 0.25 inch pipes to carry liquid nitrogen, {6} Highly oxidized copper plates. The length of the full assembly is 45 inch.

The partial pressure of nitrogen, as recorded from RGA readings, was a factor 100 lower than the total pressure reading inside the 5% model [1]. So the expected nitrogen contribution to the pixel detector gas load is $5 \cdot 10^{-9}$ mole/sec. We show that installing four liquid helium cryopumps with the section sketched in Figure 2 and having a length of 45 inch, the expected nitrogen background density into the vacuum vessel is $7 \cdot 10^{-10}$ mole/m^3 (the pressure of a gas at room

temperature and with this density is 1.3 10⁻⁸ torr). As for the water, this background density has been calculated using the outgassing rate at room temperature and not considering its reduction lowering the pixel detector temperature and with the elapsed time under vacuum. The nitrogen condensation coefficient used in this calculation is $c_{N2} \approx 0.15$.

The central part (blue) of the pump (Fig. 2) is made of five 0.2 inch stainless steel pipes {1} carrying liquid helium (4.2 K). They are covered by charcoal {2} to pump hydrogen. The charcoal capability to be degassed at room temperature is very important for this application. The gaseous helium boil-off (~20 K) goes back to the helium liquefier by the four 0.2 inch light blue pipes {3}. Four copper shields {4}, having the thickness of about 1 mm and the surface highly oxidized to have a high emissivity, are thermally coupled to these helium gas pipes. The warmer stage (red) of the cryopump is at the LN2 temperature. The liquid nitrogen flows through the four 0.25 inch red pipes {5}. The four 1 mm and high emissivity copper shields {6} are thermally coupled with the four 0.25 inch red pipes. The length of the full assembly is 45 inch.

The nitrogen molecules stick on the external surface of the four light blue panels {4}, each panel is wide 1.8 inch. The molecules also enter the section C of the cryopump by the four 0.3 inch apertures. The probability that a nitrogen molecule escapes this section C is very low, because the light blue walls {4} are at about 20 K and the black charcoal wall {2} is at 4.2 K. So we assume $c=1$ (each molecule entering the section C sticks on the cryopump walls) for the four 0.3 inch apertures and 0.15 for the condensation coefficient of the nitrogen on the external surface of the light blue walls {4}. The effective nitrogen-pumping surface of the 4 cryopumps is

$$(1.8" + \frac{0.3"}{0.15}) \times 4 \times 4 \times 45" \cong 1.8\,m^2 \,.$$

The nitrogen density n_B inside the section B reaches the steady state value when the flow of molecules pumped by this 1.8 m² effective cold surface is equal to the one released by the outgassing process ($\Phi_{N2} = 5 \cdot 10^{-9}\,mole/\sec$)

$$\Phi_{N2} = 0.15 \times (1.8\,m^2)\frac{n_B v_B}{4} \tag{5}$$

The average velocity of the nitrogen molecules inside the region B is 240 m/sec (their average temperature is near to the one of the red walls {6}) and from the (5) $n_B = 3 \cdot 10^{-10}\,mole/m^3$.

The molecular transmission probability, between the rectangular duct connecting the vacuum vessel region A with the section B of the cryopump and having the cross section of $0.37 \times 45\,inch^2$ and the length of 0.4 inch, is 0.65. The total effective area of these 16 ducts is $S_{A\_B} = 0.65 \times 4 \times 4 \times 0.37" \times 45" = 0.11\,m^2$. The steady state density n_A in the region A is such that the particle flow going from A to B minus the one going from B to A must be equal to the gas flow released by the outgassing process Φ_{N2}.

$$\Phi_{N2} = S_{A\_B} \ (n_A \frac{v_A}{4} - n_B \frac{v_B}{4}) \tag{6}$$

The particle flow leaving the section B of the four cryopumps is $S_{A\_B} \ n_B \ \frac{v_B}{4} = 2 \cdot 10^{-9} \ mole/\sec$.

Assuming that the temperature of the nitrogen in the region A is the average between the liquid nitrogen and the room temperature, the average velocity of the nitrogen molecules in this region is $v_A = 380 \ m/\sec$. The (6) gives a nitrogen density $n_A \cong 7 \cdot 10^{-10} \ mole/m^3$; a gas with this density and at the room temperature has a pressure of $1.3 \cdot 10^{-8} \ torr$.

The overall pumping speed of these four cryopumps for hydrogen at the room temperature is at least 2000 L/sec; the calculation has been done with a condensation coefficient of the hydrogen on the charcoal surface of 0.06. Note that the temperature of the hydrogen in the section C is about 20 K.

The liquid helium required to condense the gas released inside the vertex detector is negligible compared with the one necessary to run the cryopump; it depends on the apparatus design: the thermal radiation shielding, the conduction path between the cryopump and the warm vertex detector walls and, principally, on the liquid helium transfer line from the helium liquefier to the cryopumps. In a following note the detailed calculation of the liquid helium consumption can be done. A liquefier producing about 15 l/h of liquid helium has been used by the experiment E835; the liquefier was located in the AP50 building and the experiment was installed below on the antiproton accumulator ring.

2.2   Water Pump

The cold block assembly consists of the heat sink for the substrate temperature control system and the cable strain relief structure (Figure 3). Although the primary purpose of the cold block assembly is not related the vacuum system, the cold temperature of the surfaces on the assembly acts as water pumps.

Regarding the heat sink, liquid nitrogen flows through the two tubes passing through tabs. The tabs sit within the two channels. The surfaces of the cold block assembly that are readily exposed to the pixels, namely the channels and the tabs, are cold enough to act as water pumps. For each half of the carbon fiber support structure, there are 60 tabs that are the thermal connection from the substrate to the liquid nitrogen heat sink. With each tab having dimensions $4 \, cm \times 4 \, cm$ and both sides of the tab acting as a pump, the exposed surface has an area of 1900 cm². The channels that surround the tabs have a total surface area of 5200 cm².

The cable strain relief structure consists of 30 aluminum C-shaped plates. The aluminum structures are connected to the heat sink. The thermal conductance of the aluminum makes the temperature in the structure range between –195°C and –139°C, if the heat sink is at a temperature of –195°C. The surface area of one plate is 170 cm². Thus the total surface area of the strain relief structure as shown in Figure 3 that pumps water is 5000 cm². Taking into account both halves of the carbon fiber support structure and including the heat sink and the

cable strain relief, there is a **total surface area of 2.4 m^2** that acts as a water pump. Note that a secondary benefit of the cable strain relief structure is that it acts a radiation shield around the sides of the pixel detector, thus reducing the temperature of the detector and helping to reduce outgassing.
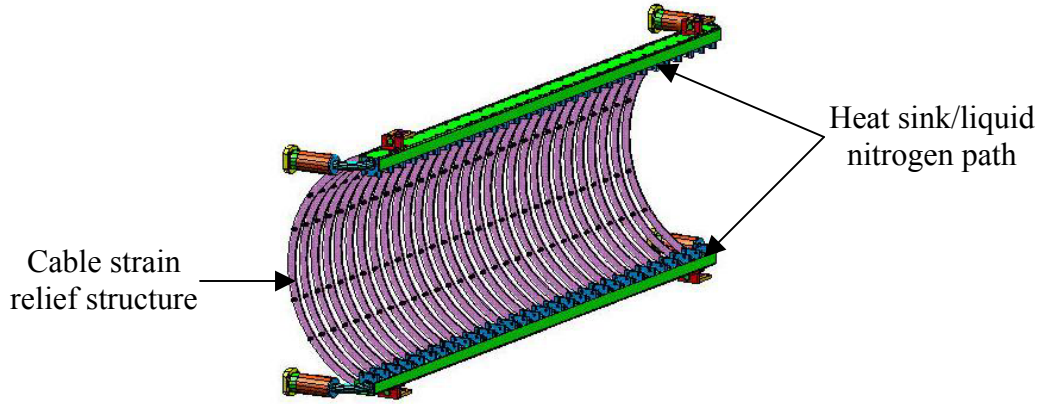

Figure 3 – Cold Block Assembly

Two cryopanels, separately cooled by liquid nitrogen, are distributed above and below the carbon fiber support cylinder (Fig. 1). The panels help in two manners. The primary purpose of the cryopanel is to pump water. The panel used in the 5% model had a pumping speed of $20,000\, L/sec$ and dimensions 63.5cm x 33cm [1]. In the real detector, each cryopanel has dimensions 33cm x 100cm. Taking into account holes in the panels for the actuator, **the total surface of both panels increases to as much as 0.6 m^2**. This assumes that only one side of the panel is exposed to the water. A secondary benefit, from surrounding the carbon fiber support cylinder, and thus the pixels, with the two cryopanels covering the other walls of the vertex detector, is reducing the temperature of the detector. Combined with the cooled strain relief structure, the cryopanels reduce the outgassing and improve the overall temperature and size stability.

Another large contribution to the water pumping comes from the thermal shields of the four liquid helium cryopumps (Fig. 2). The water molecules stick on the external surface of the four red panels {6}; each panel is wide 3.2 inch and long 45 inch. The molecules also enter the section B of the cryopump by the four 0.37 inch apertures. The probability that a water molecule escapes this section B is very low, because its red walls {6} are at 77 K and its light blue wall {4} are at about 20 K. So we assume $c=1$ (each molecule entering the section B sticks on the cryopump walls) for the four 0.37 inch apertures and a water condensation coefficient 0.4 on the external surface of the red walls {6}. The 4 cryopumps add an effective water-pumping surface of $(3.2^" + \dfrac{0.37"}{0.4}) \times 4 \times 4 \times 45" \cong \mathbf{1.9\, m^2}$.

Thus the combined effective surface of the cold block assembly, the cryopanels and the liquid helium cryopumps is 4.9 m^2. The expected background of water molecule density, obtained by the (3) with $c_w \approx 0.4$, is $n_w = 2 \cdot 10^{-9} \, mole/m^3$; a gas with this density and at the room temperature has a pressure of $3.7 \cdot 10^{-8}$ torr. Please note that this background density has been calculated using the outgassing rate at room temperature and not considering its expected significant reduction lowering the pixel detector temperature and with the elapsed time under vacuum. The nitrogen partial pressure reduced by a factor of five when the heat sink of the 5% model was cooled from 20°C to −160°C.

The pumping speed of this 4.9 m^2 effective cold surface, calculated by the (4) assuming the water molecules at room temperature (average velocity of 594 m/sec) and the condensation coefficient of 0.4, is 290,000 L/sec.

2.2.1 Cryopanel regeneration time

Assuming that each molecule occupies a surface area equal to the square of its diameter (the diameter of the water molecule is 4.6 10^{-10} m), a monolayer of water is made of 7.8 10^{-6} mole/m^2. The outgassing rate of $5 \cdot 10^{-7} \, mole/sec$ condensing on a cold surface of 4.9 m^2 makes about 1100 monolayers of water per day. The rate of growth of the ice on the cryopanels should be lower than half millimeter per year.

As a point of reference, a manufacturer of commercial cryopumps, Helix Technology, provides a defrosting interval of their waterpump. From their website, "If pumping water continuously at $1 \cdot 10^{-6}$ torr, the defrosting interval should be about every 2 months (or ~ 20 months at $1 \cdot 10^{-7}$ torr) [4]". The defrosting interval of the cryopanel in the vertex detector that is exposed to a pressure lower than $0.5 \cdot 10^{-7}$ torr should be longer than 3 years. Helix also writes: "Water capacity for a low-profile water pump is about 5 cc; for an *in-line* the capacity is about 20 cc [of condensed water] [5]". From their data, the cold panel of the *in-line* model has a cold surface of about 0.1 m^2 [6], so the water capacity is about 200 cc/m^2 or 10 mole/m^2. Assuming the same specific water capacity, it will take about 3 years to condense a flow of water molecules of $5 \cdot 10^{-7} \, mole/sec$ on the 4.9 m^2 of surface at the LN2 temperature (the total capacity is 49 mole of water).

We plan to measure the dependence of the cryopanel pumping speed from the quantity of ice developed on its surface; the total amount of water condensed on the cryopanel surface during this test will be equivalent at about 100 days of run in the presence of a constant outgassing rate of 0.01 torr L/sec.

Regarding the water condensation coefficient, Helix writes that the condensation coefficient of their pumps is 0.95: "In-line and appendage On-Board Waterpumps capture 95% of all the water molecules that actually enter the pump [7]". Note that we are using a condensation coefficient of 0.4. This lower value is considered as a safety factor since our design is totally based on the outgassing rate of the 5% model multiplied by 20.

3   Conclusion

The vertex detector cryogenic pumping system has been designed using the outgassing rate of 0.01 torr L/sec obtained from the 5% model measurements. The vertex detector vacuum specification requires a gas density lower than $5 \cdot 10^{-9}$ $mole / m^3$ regardless of the temperature. It has been showed that the expected background density of water is $n_w \cong 2 \cdot 10^{-9}$ $mole / m^3$ and that of nitrogen is $n_A \cong 7 \cdot 10^{-10}$ $mole / m^3$. (A gas with a density of $1 \cdot 10^{-9}$ $mole / m^3$ and at 300 K has a pressure of $1.9 \cdot 10^{-8}$ $toor$). The pumping speed for hydrogen of the proposed four cryopumps should be at least 2000 L/sec.

4   Pump down and regeneration procedure

This procedure assumes that it is necessary to keep the pixels always below -10 C. The temperature of all the cold surfaces must always be colder than the pixels, because we do not want to pump water on the pixel surface. It necessary to verify the quality of this regeneration process, carried with the pixel detector at a temperature lower than -10 C, and if the longer time required by the water to be sublimed is acceptable. Within this hypothesis, at the end of the regeneration procedure the vertex detector is under vacuum, pumped by the turbo pump through ~10 L/sec line[1], and cooled below -10 C by cold nitrogen gas flowing inside the cryopanels pipes. The substrate temperature control systems keep the pixels temperature at -10 C and helium gas flowing in the cryopump pipes ({1}{3} of Fig. 2) warms the charcoal.

The pump down procedure that is explained assumes that a rough vacuum is already in place. The proposed process to cool down the pixel vacuum system is:

1) Slowly feed liquid nitrogen to bring all the water pump surfaces at the liquid nitrogen temperature and wait that the pressure and temperature become stable. The pressure should decrease on 10^{-5} torr scale; at this point the majority of the background gas should be nitrogen. The substrates control system continues to maintain their temperature at -10 C. The liquid nitrogen flow in the cold block assembly must increase slowly, according with the time response of the substrate temperature control system. If the power of the temperature control system is not enough, decrease the temperature set point making sure that the pixels are the vertex detector warmer part. During the cryopanel cool down, the temperature of the helium gas in the pipes {1} and {3} decreases keeping also the charcoal warmer than the inner detector ambient.
2) Send the liquid helium to the four cryopumps and wait that the pressure and temperature become stable. The vacuum pressure should become lower than $1 \; 10^{-7}$ torr at the end of this

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[1] This pumping speed depends on the number and dimension of the pipes connecting the fore vacuum port of the cryopumps to the turbo

cool down phase. The turbo pump remains operating also when the vacuum has reached the steady state value[2].

3) Adjust the set point of the substrate temperature control system at the working value.

When the detector comes offline, the procedure to regenerate the entire BTeV Vacuum Vessel is:

1) With the turbo pump running, slowly increase the cryopump ({1}{3} of Fig. 2) temperature, decreasing the liquid helium flow rate. Their temperature must increase slowly to keep the pressure lower than 10^{-4} torr .

2) Send helium gas with controlled temperature in the helium pipes {1} and {3}. The charcoal temperature must be always sufficiently higher to avoid water condensation on them.

3) With the cryopanels still operating, pixels must be warmed in a controlled fashion to bring the substrate temperature to -10°C. If the substrate heater has not enough power send cold gas, instead of liquid nitrogen, through the cold block assembly.

4) Controlling the pressure in the vacuum vessel, increase the temperature of the of all the LN2 surfaces up to a value slightly lower than -10C.

5) Sending a leak of dry nitrogen lower than 0.01 torr L/sec, to keep the pressure lower than 10^{-3} torr , should help the regeneration process.

References

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[2] Usually there is a valve insulating the mechanical pump from the cryopump avoiding backstreaming, because of the turbo pump presence this does not apply to this case.